Sea Level Change

Chip Fletcher
Paleo Sea Level – indirect proxies
+6.6 m above present

Eemian Temperature and Sea Level

Red dots – temperature (sea surface, ice cores, pollen)
Green line – model of temperature data
Blue – B1, 2100 scenario, 1.1-2.9°C

Sea level was +6.6 m (95%) higher than today.
The world's ice is melting
Antarctica is losing Ice
Rate of Antarctic ice loss has tripled since 2004

Velicogna et al., 2014, Regional acceleration in ice mass loss from Greenland and Antarctica using GRACE time-variable gravity data, GRL, 10.1002/2014GL061052
“Irreversible retreat”

West Antarctic Ice Sheet “has passed the point of no return”

...a rise in global sea level of at least 2 ft over two centuries, and ultimately 10-13 feet, may now be inevitable.

Meltwater Pulse

Post-Glacial Sea Level Rise

- Santa Catarina
- Rio de Janeiro
- Senegal
- Malacca Straits
- Australia
- Jamaica
- Tahiti
- Huon Peninsula
- Barbados
- Sunda/Vietnam Shelf

Sea Level Change (m)

Thousands of Years Ago
How do these ice sheets fail?
Greenland is losing Ice
Rate of Greenland ice loss has doubled since 2009

Velicogna et al., 2014, Regional acceleration in ice mass loss from Greenland and Antarctica using GRACE time-variable gravity data, GRL, 10.1002/2014GL061052
Mountain glaciers – all regions are losing mass
combined loss of Greenland and Antarctica
= 30% of observed sea level rise

Gardner et al., 2013, A reconciled estimate of glacier contributions to sea level rise: Science: v. 340 no. 6134 pp. 852-857 DOI: 10.1126/science.1234532
Thermal Expansion

3560 Floats
22-May-2014

Argo
Global warming not slowing – it's speeding up

90% of excess heat stored in oceans

Ocean Warming: 0–700-m 1971–2010 trends

- Warming almost everywhere
- Some isolated regions of cooling
- Regional patterns owing to:
  - Changes & variations in winds
  - Changes & variations in air-sea heat fluxes

Near-surface ocean warms more than the subsurface ocean
- Increase in thermal stratification (about 4% over 4 decades)
- Constructed from gridded product
- World Ocean Atlas 2009 update
Deep & Abyssal Ocean Warming

- Basin-averaged warming rates for 4000–6000-m
- CLIVAR repeats of WOCE hydrographic sections
- 1980s–2000s data
- centered 1992–2005
- Also assessed 2000–6000-m value

- 700–2000-m curve from Levitus et al. (2012) – all available data
Contributions to GMSLR Rise (GMSLR)

- Ocean Warming about 1/3 of observed GMSLR 1993–2010
- Melting Ice about 1/2 of observed GMSLR 1993–2010
- Sea Level Budget balanced (mass addition + thermal expansion = observed)
- Strong contrast with energy storage budget where ocean warming dominates
Satellite Altimetry – global average 3.2 mm/yr
Flooding
USAPI
• Human communities dependent on external lifelines
• Rising temperatures, changing rainfall
• Threats to biodiversity
  • Alien species
  • Extinction
• Rising sea level, ocean acidification, SST
• Changing storminess
<table>
<thead>
<tr>
<th>Year</th>
<th>Min</th>
<th>Mean</th>
<th>Max</th>
</tr>
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<tbody>
<tr>
<td>2030</td>
<td>9 cm</td>
<td>15 cm</td>
<td>21 cm</td>
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<tr>
<td>2050</td>
<td>18 cm</td>
<td>30 cm</td>
<td>44 cm</td>
</tr>
<tr>
<td>2100</td>
<td>48 cm</td>
<td>87 cm</td>
<td>141 cm</td>
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</tbody>
</table>

Honolulu Projected Heights (95% confidence)

According to recent geologic history, for every 1°F of warming, sea level will rise 4.2 ft in the long run (we have already warmed 1.6°F)

NOAA SLR viewer
http://www.csc.noaa.gov/digitalcoast/tools/slrviewer

Extreme Tides

Storm drains back up at high tide.
Sea level rise will cause drainage problems

Waikiki, Outrigger Reef Hotel
Groundwater Inundation

Marine and Groundwater Inundation

At 0.66 m, 69% of total flooded area is due to groundwater inundation

Total flooded areas including groundwater inundation at MHHW

- at current SL
- +0.33 m SLR
- +0.66 m SLR
- +1.0 m SLR

Sea-Level = + 0 [m]
Drainage problems
Isolated communities
Evacuation routes and shelters
Salt water intrusion
New wetlands
Drainage problems
Road access
Wave overtopping
Coastal erosion
Sea level +3 ft
Isolated communities
Flash flooding
Federal agencies plan for rising seas

• Use data and methods “informed by best-available, actionable climate science”;
• Build 2 ft above the 100-year flood elevation for standard projects, and 3 ft above for critical buildings (hospitals and evacuation centers);
• Build to the 500-year flood elevation.
Tropical cyclones to increase

Figure 1

<table>
<thead>
<tr>
<th>tropical cyclone genesis, tropical cyclone tracks, and nonlinearity</th>
</tr>
</thead>
<tbody>
<tr>
<td>contributions substantially to the local decreases</td>
</tr>
<tr>
<td>mean easterly steering flow (between 12 °N and 20 °N)</td>
</tr>
<tr>
<td>large-scale steering flow. Projected future changes in the</td>
</tr>
<tr>
<td>tropical cyclone track effect (equation 4)</td>
</tr>
<tr>
<td>origin analysis (equation 3), which is the combined effect</td>
</tr>
<tr>
<td>contributions of each term to the projected increase in TCF</td>
</tr>
<tr>
<td>change (that is, at 10 °N). The changes in tropical cyclone</td>
</tr>
<tr>
<td>genesis in the southeast domain. The changes in tropical</td>
</tr>
<tr>
<td>cyclone genesis in the southeast domain tend to propagate</td>
</tr>
<tr>
<td>other effects, indicating that tropical cyclones generated</td>
</tr>
<tr>
<td>southeast contribute substantially to the increase in TCF</td>
</tr>
</tbody>
</table>

Murakami, H., et al., 2013 Projected increase in tropical cyclones near Hawaii, Nature Climate Change, May 5, DOI:10.1038/NCLIMTE1890
Tropical cyclone maximum intensity shifting poleward by 35 miles/decade

Kossin et al., 2014 The poleward migration of the location of tropical cyclone maximum intensity, Nature, 509, 349–352 (15 May)
Water, Water, Everywhere: Sea Level Rise in Miami

Like many low-lying coastal cities around the world, Miami is threatened by rising seas. Whether the majority of the cause is anthropogenic or natural, the end result is indisputable: sea level is rising and it is due to climate change. It is not a political issue, nor does it matter if someone believes in it or not.
Verified High Water Levels at Virginia Key, FL

- Average increase over last 15 years: 0.30"/year
- Average increase over last 10 years: 0.47"/year
- Average increase over last 5 years: 1.27"/year

Events:
- 10/15/99 Hurricane Iniki
- 10/24/05 Hurricane Wilma
- 9/26/08 Autumn Tide
- 10/30/12 Autumn Tide

Depth Above MLLW (feet)
New York City Could See Up To Six Feet Of Sea Level Rise This Century: Report

The Huffington Post | By James Gerken

Posted: 02/17/2015 6:24 pm EST | Updated: 02/17/2015 7:59 pm EST

A new report from the New York City Panel on Climate Change warns of growing climate change threats to NYC. (AP Photo/John Minchillo) | ASSOCIATED PRESS

Climate change is already impacting New York City with rising temperatures and sea levels, which will only worsen as the century continues, according to a report released Tuesday from a panel of scientific experts.

In its 2015 report, the New York City Panel on Climate Change found that the most vulnerable are the elderly, the poor, and communities of color. They are already experiencing higher temperatures, more intense rainfall, and increased flooding.
EXPLANATION

Historical shoreline

- January, 1928
- Topographic sheet, 1932
- September, 1949
- October, 1958
- April, 1967
- March, 1971
- March, 1975
- February, 1988
- July, 1996
- June, 2006

- Transect, 20-meter spacing
Historical Shoreline Data

Cross-shore position over time

EXPLANATION
- Shoreline position with errors
- Regression Line


Cross-shore Position (m)
Future erosion hazards?
Simply extrapolating the trend is not sufficient
Modeling sea level rise impacts

\[ R = \left[ \frac{L}{(B+h)} \right] S \]

Bruun Rule, 1962, 1988
Even after a century of SLR, many Hawaii beaches are accreting.
Sediment loss with sea level rise
Sediment gain with sea level rise
Example: Accreting shoreline

Transect 143, Kailua

Historic trend = 0.33 ± 0.15 m/yr
Example: Eroding shoreline

Transect 120, Hauula

Historic trend = $-0.16 \pm 0.03 \text{ m/yr}$
Study Areas

- Ehukai & Sunset
- Hauula
- Kailua
- Makaha
- Poipu
- Lydgate
- Kaanapali
- Baldwin
- North Kihei
South Hauula
Change Rates – S. Hauula

Rates (with 80% confidence): Hauula - South
[2005], [2050], [2100]

Shoreline Change Rate (ft/yr)

Transect
Net Change – S. Hauula
### Kauai, Oahu, Maui

<table>
<thead>
<tr>
<th>Historical Rate</th>
<th>2030</th>
<th>2050</th>
<th>2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.8 ft/yr</td>
<td>-1.1 to -1.3 ft/yr</td>
<td>-1.2 to -1.6 ft/yr</td>
<td>-1.6 to -2.3 ft/yr</td>
</tr>
<tr>
<td><strong>Future rate of change</strong></td>
<td>2030</td>
<td>2050</td>
<td>2100</td>
</tr>
<tr>
<td></td>
<td>-1.1 to -1.3 ft/yr</td>
<td>-1.2 to -1.6 ft/yr</td>
<td>-1.6 to -2.3 ft/yr</td>
</tr>
<tr>
<td><strong>Future Absolute change</strong></td>
<td>2030</td>
<td>2050</td>
<td>2100</td>
</tr>
<tr>
<td></td>
<td>-24.8 to -29.8 ft</td>
<td>-47 to -58.6 ft</td>
<td>-115.5 to -156.9 ft</td>
</tr>
</tbody>
</table>
Haena
Projected erosion hazards, 2050 and 2100
Baldwin Beach
Projected erosion hazards, 2050 and 2100
Baldwin Beach
Projected erosion hazards, 2050 and 2100

Geology
- A: Alluvium
- D: Dune
- V: Volcanics

Shoreline Type
- Yellow: Riprap
- Green: Gravel beaches
- Blue: Mixed sand & gravel beaches
- Light blue: Coarse-grained sand beaches
- Purple: Exposed wave-cut platforms in bedrock
Baldwin Beach
Projected erosion hazards, 2050 and 2100

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Public Infrastructure

Tax Map Keys (TMKs)
Baldwin Beach
Projected erosion hazards, 2050 and 2100

Geology
- Alluvium (A)
- Dune (D)
- Volcanics (V)

Shoreline Type
- Riprap
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Public Infrastructure
- Roads

Tax Map Keys (TMKs)
Baldwin Beach
Projected erosion hazards, 2050 and 2100

Legend
- 2050 erosion hazard
- 2100 erosion hazard
- Transects
- Shoreline

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- Parks
- Roads
- Tax Map Keys (TMKs)
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Projected erosion hazards, 2050 and 2100

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- 2050 erosion hazard
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Public Infrastructure
- Parks
- Roads
- Tax Map Keys (TMKs)
**Baldwin Beach**

**Projected Erosion Hazards, 2050 and 2100**

**Shoreline Change**

Historically (1975 to 2007), 57% of the beach eroded and 43% accreted. The overall average rate of shoreline recession was 0.4 ± 0.1 ft/yr. Accretion was limited to the western half of Baldwin and a small section in the middle of Pala Bay. Modeled shoreline response to sea level rise indicates that 77% of the beach will experience erosion of -1.1 ± 0.1 ft/yr by 2050 and 82% will erode averaging -1.6 ± 0.2 ft/yr by 2100. Net shoreline change will average -0.9 ± 0.2 ft/yr by 2050 and -1.0 ± 0.7 ft/yr by 2100.

**Modelling Beach Change**

Future sea level predictions using the RCP 6.0 scenario (IPCC AR5, 2014) are converted to shoreline recession distances using the Davidson-Arnott geometric model (Davidson-Arnott, 2005). Recession values are adjusted to reflect local sea level and sediment availability using tide-gauge records and historical shoreline change rates (Fletcher et al., 2013).
More stable

More erosional
Sea level rise Miami